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REVERBERATION CHARACTERISTICS OF A LARGE WELDED STEEL SHIELDED ENCLOSURE

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13. ABSTRACT (Maximum 200 words)

For the past several years there has been an increasing interest in the possibility of testing large items such as aircraft in a reverberation chamber. One concern has been the scaleability of a chamber's operational characteristics. To test a reasonably large aircraft, a chamber would have to have a volume of 5×10^4 m^3 or greater. NSWCDD was given an opportunity to test an empty cavity with a volume of about 2500 m^3. The Hewlett Packard Company made available their empty, 10-m, semi-anechoic chamber during the final stages of construction. Data collection to satisfy a limited, high priority set of objectives was limited to one weekend. Frequency range was 30 MHz to 18 GHz. (Due to tuner effectiveness and signal-to-noise level obtained with the limited input power available, the effective frequency coverage was 90 MHz to 6 GHz.) Within acceptable measurement uncertainty, the cavity electromagnetic environment was isotropic, randomly polarized and uniform over the frequency interval tested. The cavity quality factor was somewhat lower than expected. Within the limited data set, there were no significant departures from the theoretical scaleability.

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reverberation chamber, isotropy, random polarization, field uniformity, chamber volume, Kolmogorov-Smirnov test, electromagnetic test facility

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FOREWORD

The measurements discussed in this report were obtained by the Systems Electromagnetic Effects Branch (J52) of the Electromagnetic Effects Division of the Naval Surface Warfare Center, Dahlgren Division. The work was partially funded by the Naval Air Warfare Center, Patuxent River, MD.

The test was conducted during the final stages of construction of a 10-m, semi-anechoic chamber at the Hewlett Packard Company facility at Roseville, CA. The welded steel cavity was completed and the shielded access doors installed. No shielding effectiveness tests had been performed. No absorber material had been installed. At this stage of completion the chamber provided an opportunity to investigate the electromagnetic characteristics of a large shielded enclosure.

The authors wish to acknowledge Kenneth Hall of Hewlett Packard and Michael Caruso of Lindgren RF Enclosures, Inc., for their assistance in obtaining access to the facility and in planning and conducting the test.

This report has been reviewed by William Lucado, Head, Systems Electromagnetic Effects Branch; Leonard Fontenot, Head, Electromagnetic Effects Division; and Dr. Lisle H. Russell, Chief Scientist, Joint Warfare Applications Department.

Approved by:

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Joint Warfare Applications Department

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

TABLES

1.0 INTRODUCTION

1.1 BACKGROUND

As reverberation chambers become more common for radiated emission and immunity testing, the interest in testing larger systems has increased. In particular, there is a potential demand for testing aircraft. In addition to the common application of reverberation chambers for testing individual avionics systems, a large chamber could be used to determine the aircraft shielding effectiveness for all aspect angles over a large frequency range. It may also be possible to expose an aircraft to the full threat high intensity radiated field (HIRF) environment.

A reverberation chamber test is intrinsically a statistical test. In the theoretical limit, the electromagnetic environment (EME) in a reverberation chamber is isotropic and randomly polarized and homogeneous throughout the working volume.[1,2] Any system tested in a properly operating reverberation chamber will be exposed to an all-aspect-angle EME of the same average energy throughout the working volume. In order to provide this EME, a cavity must be sufficiently multimoded. In addition, there must be a mechanism to excite an adequate number of independent modes. The cavity should also be free of unnecessary loss mechanisms such as absorbers or apertures.

The requirement that the cavity be multi-moded implies there is a lowest usable frequency (LUF) for any reverberation chamber test facility. The LUF depends primarily on the chamber dimensions since they define the modal structure as a function of frequency. Another important factor is the effectiveness of the mode excitation technique. Several mode excitation techniques are available. The most common technique is mode excitation using a rotatable metal tuner which changes the cavity boundary conditions.

The theory of reverberation chambers also predicts that all complex cavities are statistically equivalent.[2] This implies that variations in cavity configuration such as changing the geometry of the components of a system under test should not change the test EME. It also implies that the EME in all properly operating reverberation chambers should be statistically equivalent.

The NSWCDD maintains a data base of reverberation chambers worldwide. This data consists of stirring ratio data at 1 GHz. The data base demonstrates that, within measurement uncertainty, the EME of all the chambers in the data base agree with the theoretical predictions and with each other.[3] The volume of the chambers in the data base vary by a factor of four. Theory predicts and the data base suggests that a very large chamber, one sufficiently large to test an aircraft, should have the same statistical EME.

However the largest chamber in the data base has a volume of about 200 m³. A chamber exists with a volume of almost 300 m³ but is not yet included in the database. In order to test a reasonably large aircraft, a facility with a volume of more than 100 times that of the largest chamber currently in the data base would be required. Therefore the expected performance in an expensive facility would be based on a large extrapolation from current reverberation chamber performance. It is clear that characterization data on the EME in one or more intermediate sized chambers are desirable.

This report describes an EME characterization test on a shielded enclosure with a volume of approximately 2500 m³. The test was performed within a limited window of opportunity during the construction of the facility. Section 1.2 describes the shielded enclosure. Sections 1.3 and 2.0 define the test objectives and discuss the experimental approach respectively. Section 3.0 presents the test results. Sections 4.0 and 5.0 present the conclusions and recommendations respectively.

1.2 TEST CHAMBER

The Hewlett Packard Company contracted for the construction of a 10-m, semi-anechoic chamber. Absorbing material will line a welded steel shielded enclosure. The basic shielded enclosure was made available to NSWCDD during the final stages of construction. The basic cavity construction was complete and the shielded doors installed. No shielding effectiveness tests had been performed. The NSWCDD had access to the facility for a characterization test for a two day period prior to installation of the absorbing material.

Figure 1 shows the basic configuration of the shielded enclosure as tested. The cavity dimensions are 8 x 14.7 x 20 m for a volume of 2354 m³. An additional basement utility cavity with dimensions of 2.8 x 7.8 x 8.7 m and a volume of 192 m³ was open to the main cavity and was accessible during this stage of construction. The total volume of the shielded enclosure, in excess of 2500 m³, provided an opportunity for characterizing an intermediate sized cavity.

1.3 TEST OBJECTIVES

The objectives are listed in priority order to reflect the limited test time available:

- Characterize the statistical distribution function for the EME in the chamber at selected frequencies.

- Characterize the cavity quality factor (Q) at selected frequencies from 50 MHz to 18 GHz .

- Estimate the LUF as a reverberation chamber.

- Characterize the uniformity of the cavity EME at selected frequencies.

- Characterize the cavity modal structure at selected frequencies.
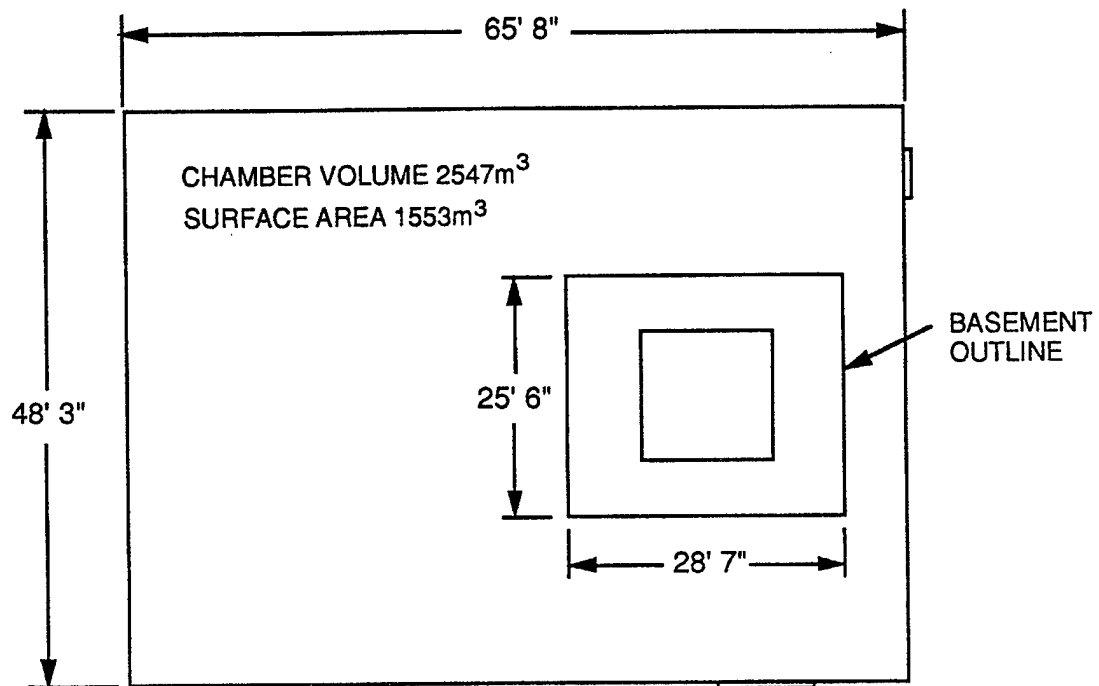
TOP VIEW
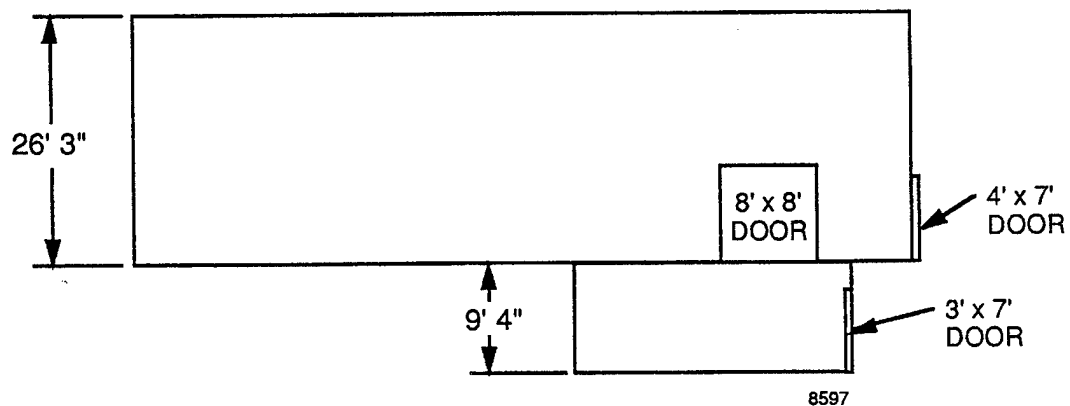
SIDE VIEW

FIGURE 1. SIDE AND TOP VIEWS OF SHIELDED ENCLOSURE

2.0 APPROACH

Figure 2 shows the test setup and Table 1 shows the equipment list. The signal generator provided a +15 dBm signal which could be frequency swept or stepped, in bands, over the frequency range of 10 MHz to 18 GHz. Above 1 GHz a linear, 20 dB preamplifier increased the available received power to the spectrum analyzer. However, the losses in the long runs of semi-rigid cable necessary to reach measurement points throughout the large chamber restricted the upper frequencies investigated. Data began to have noise problems above 5 GHz which made statistical analysis marginal. No data was collected above 8 GHz and most data collection was limited to 6 GHz.
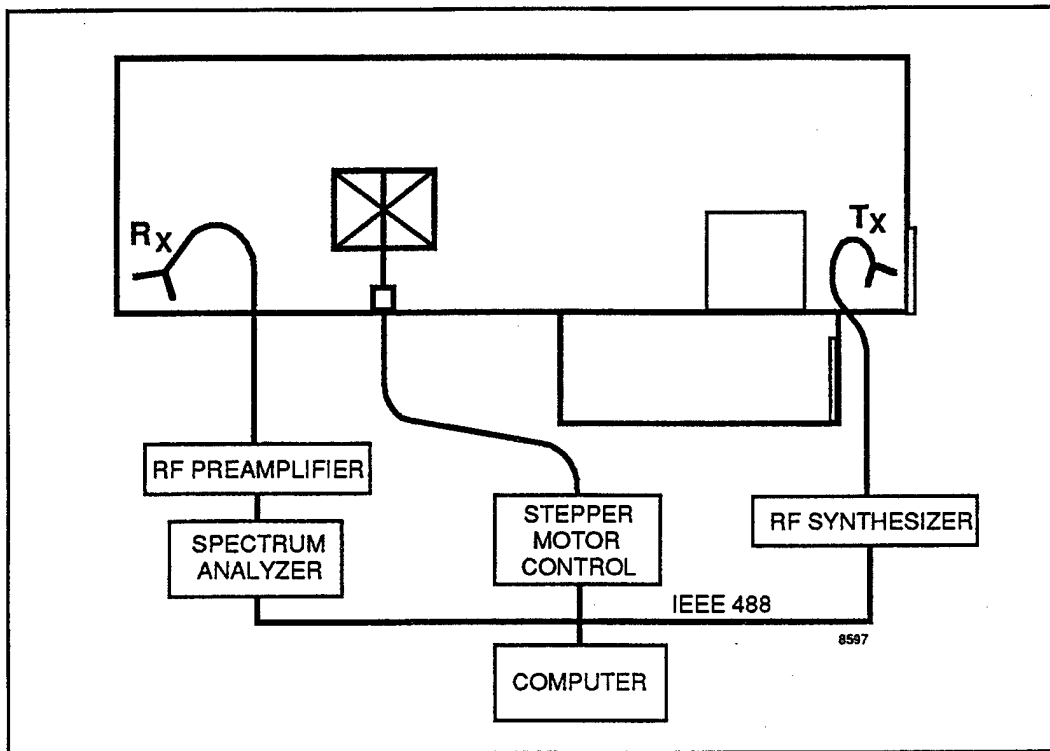

FIGURE 2. SCHEMATIC OF TEST SETUP

TABLE 1. EQUIPMENT LIST

Equipment	No.	Model
Gigatronics Universal Sweeper	1	Model 7300
Hewlett Packard Spectrum Analyzer	1	HP 8562A
Hewlett Packard Microwave Amplifier	1	HP 8349B
Rhodes & Schwartz Bilog Antennas	2	HL 023A1
Rhodes & Schwartz Log Periodic Antennas	2	HL 023
Eaton Dual Ridged Horn Antennas	2	

An input signal was introduced into the cavity by a transmit (TX) antenna. A receive (RX) antenna sampled the cavity EME. The TX and RX antennas were bilogs (30 to 1000 MHz band coverage) and log periodics (80 to 1000 MHz band coverage) for frequencies below 1 GHz and dual ridged horns (1 to 18 GHz band coverage) for frequencies above 1 GHz. The received signal was measured with a spectrum analyzer (SA) and the data recorded on disk. The instrumentation was under computer control. Automated data collection software optimized the collection efficiency. A software problem which was not resolvable on-site prevented collection of frequency stepping data in the interval 60 - 90 MHz.

A 4 x 8 ft aluminum foil covered styrofoam panel served as a rotatable tuner. The tuner had side panels to provide reflections to all cavity surfaces during rotation. The tuner changed the cavity boundary conditions as it rotated and provided the mechanism for exciting independent cavity modes. The tuner was driven by a shielded stepper motor. The tuner was too small to effect the boundary conditions associated with the low frequency modes in the cavity. The low frequency performance of the tuner limited the investigation of the distribution functions to frequencies greater than 100 MHz.

Stirring ratio (SR) measurements comprise the major portion of the data. A SR measurement consisted of sampling the cavity EME at a selected frequency at 600 tuner positions over a 20 second period of rotation. During the measurement the TX and RX antenna positions were fixed. A typical SR data trace at 1 GHz is shown in Figure 3.

A SR measurement provides the maximum to minimum power density ratio which is the definition of SR. The SR can be compared to the commonly accepted guideline of at least 20 dB for proper operation of a reverberation chamber.[4] Several other parameters can be derived from the SR data. These include the average power density which is the single parameter necessary to characterize the EME distribution; the peak to average (P/A) ratio; and, the standard deviation of the data.

The quality factor, Q, of the cavity can be calculated from the average value of the SR data.

The LUF depends on the cavity dimensions and the effectiveness of the mode excitation technique. Operationally the lowest frequency at which there is an acceptable field uniformity can be designated the LUF.

A measurement configuration consisted of a unique location, orientation, and polarization for the TX and RX antennas. The uniformity of the EME in the chamber can be estimated by comparing the average power density of SR measurements from several different configurations. The available test time limited the number of configurations that could be accomplished. For most SR data three independent TX/RX antenna configurations are available.
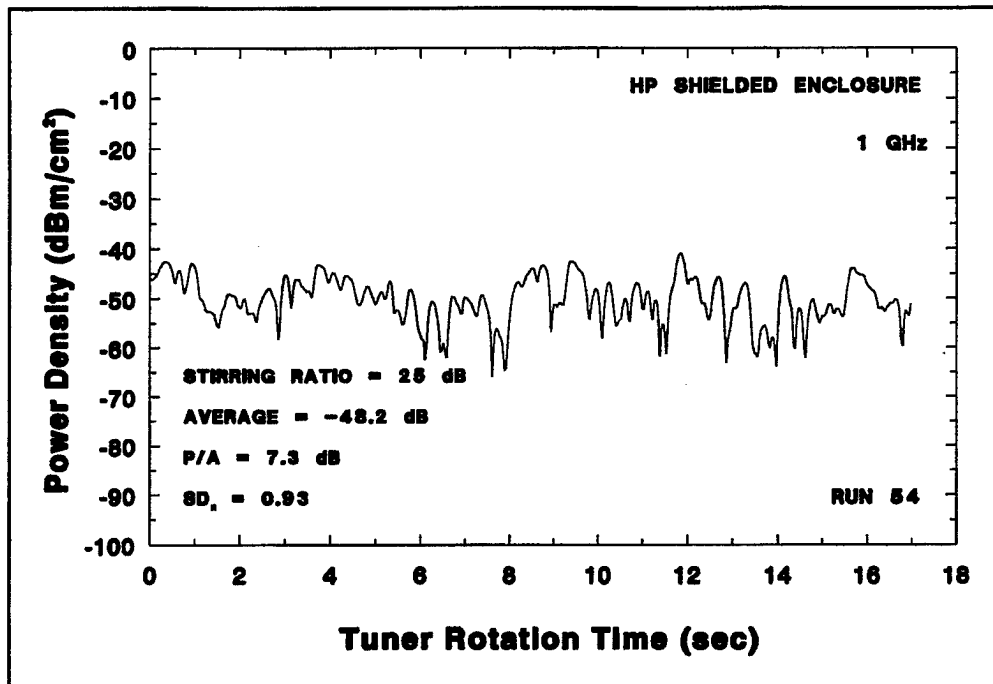
FIGURE 3. TYPICAL STIRRING RATIO DATA

The cavity modal structure is important since it impacts the excitation and/or sampling requirements to obtain a sufficient number of independent samples. The cavity modal structure was investigated at selected frequencies by frequency stepping over narrow bandwidths (BWs). Frequency step sizes were initially selected from Figure 4 which shows the expected mode spacing developed during test planning based on the theoretical mode density and estimated Q effects. Check runs were made to verify the appropriateness of the selected step size as well as to optimize the data collected within the time available.

3.0 RESULTS

The cavity EME is characterized using several parameters. The first parameter is the SR. As discussed earlier, a common guideline for proper operation of a reverberation chamber is a SR > 20 dB. Figure 5 shows the SR as a function of frequency. The triangular marker shows the SR for the data in Figure 3. The square markers show the range of the SR for the different TX/RX antenna configurations. In most cases, noise corrupted the SR data above about 5 GHz. In general, above 100 MHz the SRs exceed 20 dB and therefore satisfy one of the guidelines for a properly operating reverberation chamber. At low frequencies the low SRs are attributed to poor tuner performance.

In a properly operating reverberation chamber the peak to average (P/A) ratio is a random variable whose expected value depends on the number of independent data samples. No analysis of the correlation between the SR data samples has been accomplished. An upper bound of 8.4 dB for
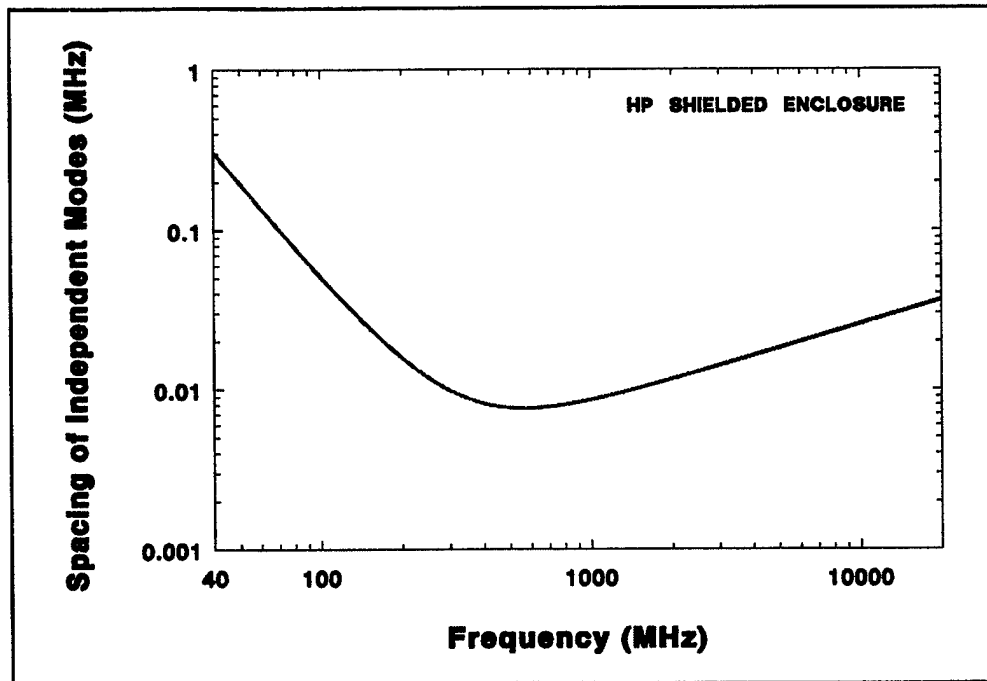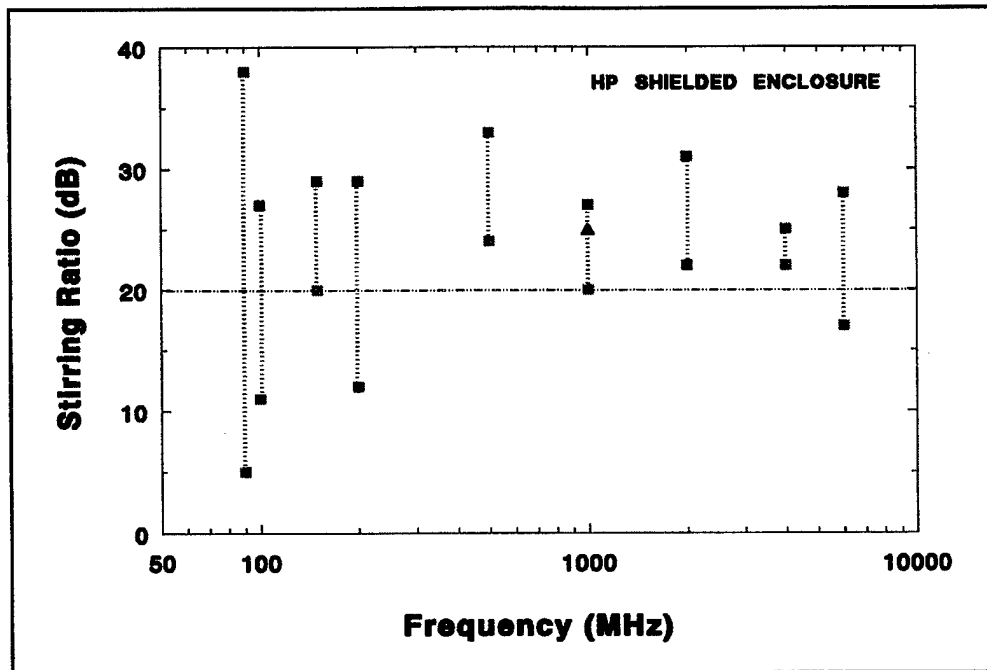
FIGURE 4. PREDICTED MODAL SPACING

FIGURE 5. STIRRING RATIO AS A FUNCTION OF FREQUENCY

the expected value assumes all 600 SR data sample are independent. Both theory and experiment indicate typical variations of 1 - 2 dB about the expected value.

The triangular marker in Figure 6 shows the P/A ratio for the data in Figure 3. The square markers show the P/A ratio for other data. The data in Figure 6 show that except at low frequencies, the P/A ratios are in general agreement with the expectations from theory and from other reverberation chambers.

The normalized standard deviation, σ_n, of the EME is another measure of how close the cavity distribution function approaches the theoretical distribution. The σ_n of the data in Figure 3 is shown as the triangular marker in Figure 7. The theoretical value for σ_n is 1 and the typical range for other chambers is 0.92 to 0.98. The data in Figure 7 shows this cavity had greater variation than is common for chambers in the data base. Low values of σ_n have been associated with unstirred energy.[5,6] While this issue has not been resolved, low values of σ_n are likely caused by tuners whose relative dimensions are small compared to the cavity dimensions. The tuner in this test was much smaller relative to cavity dimensions than any chamber in the NSWCDD data base. This is a relatively new concept for tuner design and requires further study. A few operating chambers have values as high as 1.1 at some frequencies. The implications of σ_n values greater than one are under investigation.

A more rigorous evaluation of the EME can be obtained by comparing the distribution of the 600 EME data samples to the theoretically predicted values.[2] Theory predicts[1,2] that the SR data of Figure 3 should be described by a two-degree-of-freedom chi-square distribution function. The data could be compared to the probability density function for the distribution. While this is a common approach, it suffers from the arbitrariness of the bin size in which the data is apportioned. An alternative is to compare the data to the cumulative distribution function. For the cumulative distribution the data is plotted in 600 (the sample size) steps from the minimum value (-66 dBm/cm^2 in Figure 3) to the maximum value (-41 dBm/cm^2). The cumulative distribution represents the probability that the power density is equal to or less than a specified value. Since the chi-square distribution function is totally characterized by its mean, it is convenient to plot the data as the mean normalized power density. This step involves no loss of generality, and permits comparison of experimental data from any reverberation chamber as well as comparison to theory. Figure 8 shows the data from Figure 3 plotted as the mean normalized cumulative distribution on a linear scale. The theoretical distribution function is also shown for comparison. The agreement between the measured and the theoretical distributions can be estimated from a visual comparison of the two curves. A more rigorous evaluation involves performing a statistical goodness-of-fit test. The Kolmogorov-Smirnov (K-S) test was applied to the measured data in Figure 8. The data marginally passed the K-S test. As apparent from the agreement between the measured data and the theory in Figure 8, the K-S test is a conservative test. As is common with other reverberation chambers, only a limited number of data runs passed the conservative K-S test.
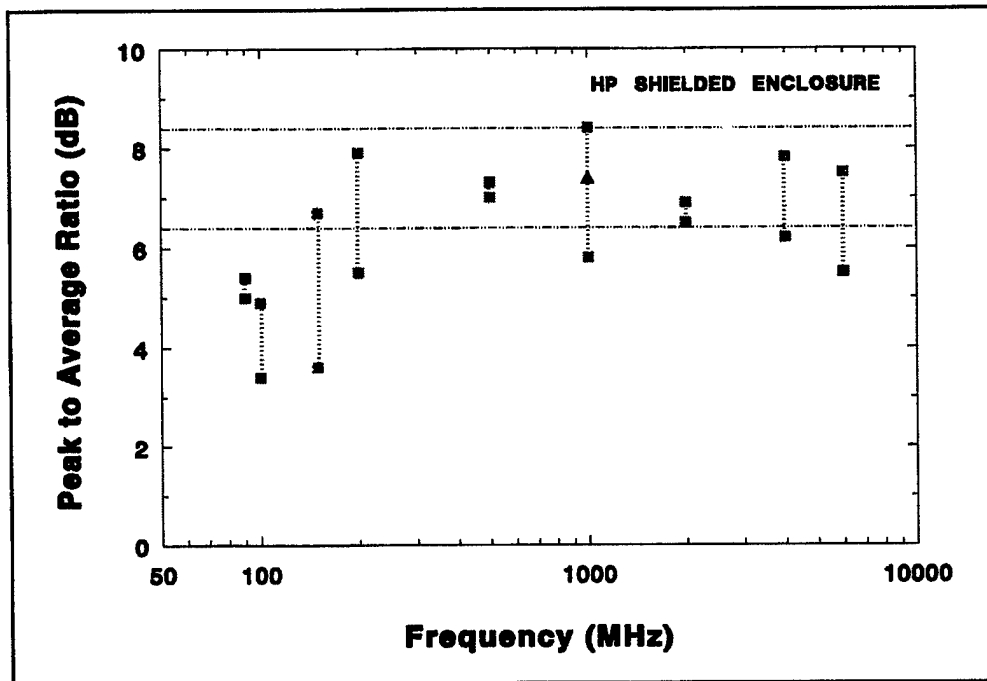
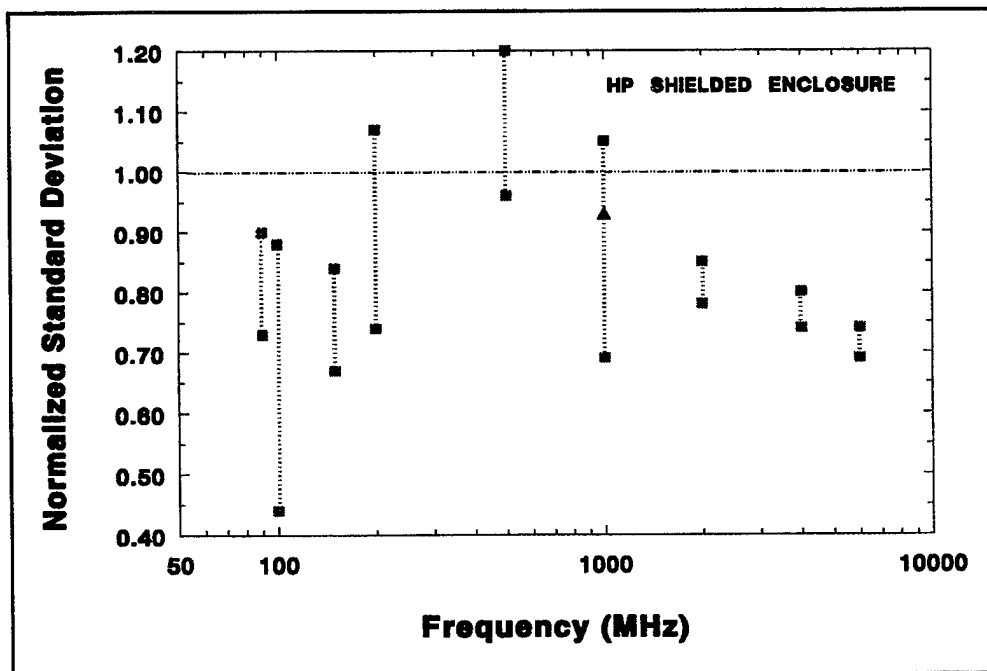FIGURE 6. PEAK TO AVERAGE RATIO AS A FUNCTION OF FREQUENCY

FIGURE 7. NORMALIZED STANDARD DEVIATION AS A FUNCTION
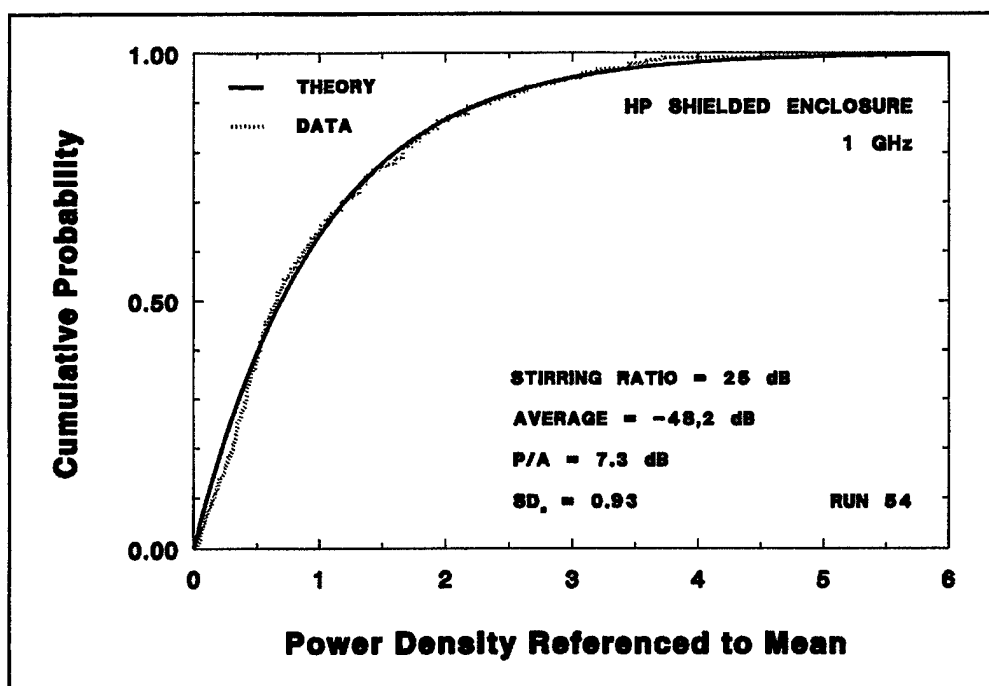OF FREQUENCY

FIGURE 8. CUMULATIVE DISTRIBUTION OF STIRRING RATIO DATA

The SR, the P/A ratio, the σ_n, and the agreement between the measured and theoretical distribution functions indicate that the EME in this large cavity is in good agreement with the EME from other operating reverberation chambers.

The cavity Q was calculated from SR data using[4]

$$Q = (16 \, \pi^2 \, V / \lambda^3) \, (P_{ave \, rec} / P_{in})$$ (1)

where V is the volume of the chamber,
$P_{ave \, rec}$ is the average received power, and
P_{in} is the input power to the chamber.

The values of Q at each frequency are represented by the triangles in Figure 9. The solid line in Figure 9 is the Q calculated using Equation (2) which depends on the RX antenna as shown in equation (3) and the chamber characteristics as shown in Equation (4).[7]

$$Q = 1/(\, 1/Q_{ant} + 1/Q_{wall} \,)$$ (2)

$$Q_{ant} = 16 \, \pi^2 \, V / \lambda^3$$ (3)

$$Q_{wall} = 3 \, V / (2 \, \mu_{rel} \, S \, \delta)$$ (4)

where μ_{rel} is the relative permeability of the wall material,
S is the surface area of the chamber, and
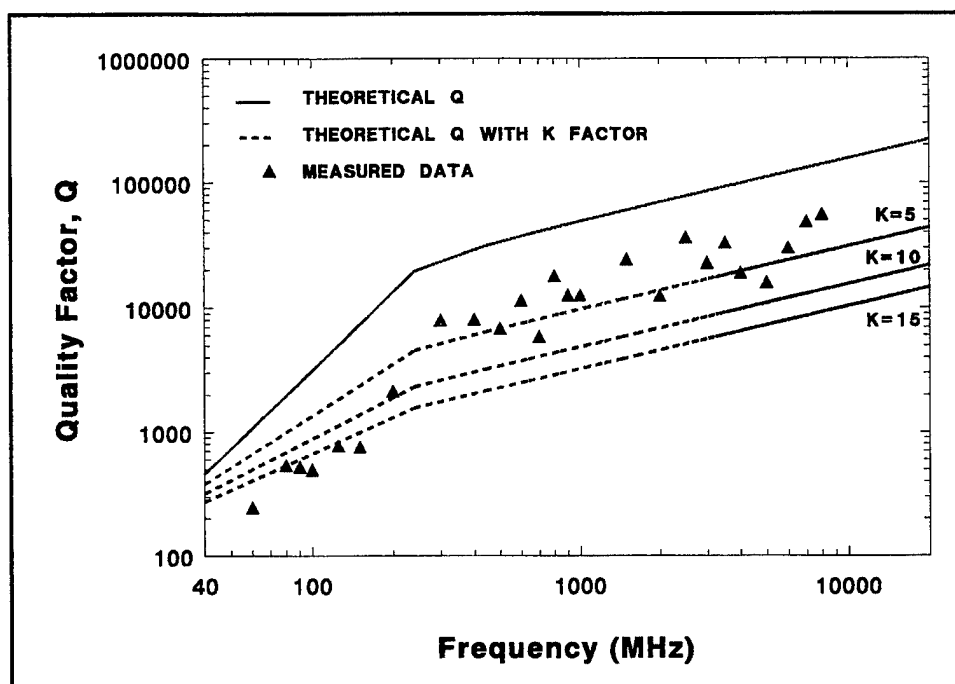δ is the skin depth of the wall material.

10

FIGURE 9. CHAMBER QUALITY FACTOR

The relative permeability was assumed to be 1. The skin depth was calculated from

$$\delta = (2/ \omega \mu \sigma)^{0.5}$$ (5)

where ω is the angular frequency, and
σ is the conductivity.

A minimum handbook value was assumed for the conductivity of the steel chamber.

Since to date no chamber has yielded a measured Q that matches the theoretical Q, a parameter, the K factor, has been developed as a measure of comparison between the theoretical Q and the measured Q for a given chamber. The K factor is defined as

$$K \equiv Q_{theoretical} / Q_{measured}$$ (6)

Typical K values are on the order of 5 or less.[8] The K values for the HP chamber were on the order of 3 to 15 as shown by the dashed lines of Figure 9. The high K factors warrant further investigation. They indicate that more power may be necessary to obtain a desired field strength in the chamber than might be expected from the current data base.

The chamber calibration factor, which is defined as the maximum power density generated by injecting 1 watt of power into the chamber, is a useful tool for measuring the efficiency of a chamber to generate high field levels. The chamber calibration factor shown in Figure 10, has units of $(mW/cm^2)/watt$ and is based on the maximum power received at each frequency tested. Using the
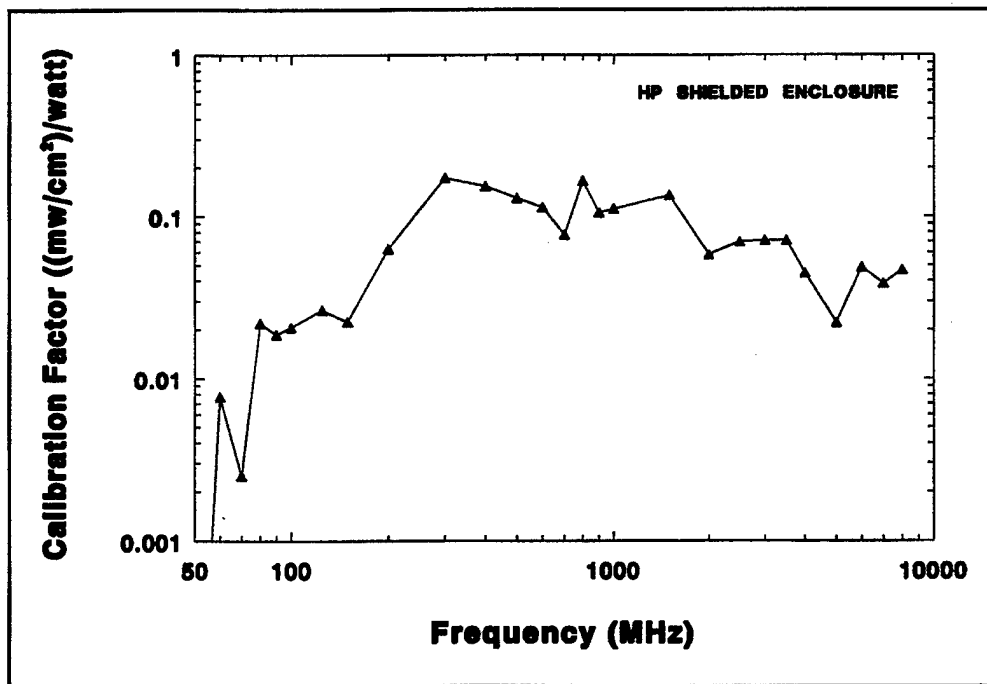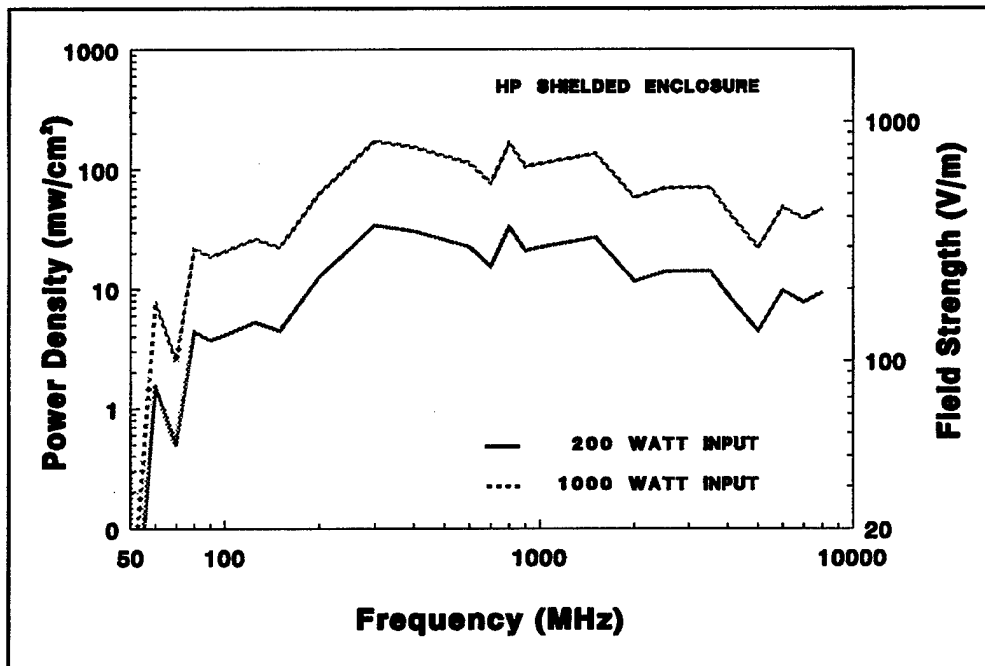
FIGURE 10. CHAMBER CALIBRATION FACTOR

FIGURE 11. PREDICTED CHAMBER ELECTROMAGNETIC ENVIRONMENT
LEVELS ACHIEVABLE WITH 200 AND 1000 WATT AMPLIFIERS

chamber calibration factor, the field levels that could be generated using 200 watt and 1000 watt amplifiers can be determined from the curves in Figure 11. Figure 11 shows that field strengths in excess of 200 V/m could be obtained using 200 watt amplifiers. Field strengths in excess of 500 V/m could be obtained using 1000 watt amplifiers. The optimum (most efficient) frequencies range from 150 to 4500 MHz.

A commonly accepted guideline for the LUF is the frequency at which the cavity supports 60 modes.[4] For this cavity, 60 modes occurs at about 45 MHz. Operationally, the LUF also depends on the effectiveness of the mode mixing technique. For rotatable metal tuners, a commonly accepted guideline[4] is that frequency at which the minimum tuner dimension is $\lambda/2$. However, it is well known that the larger the tuner, the better. Assuming that the orientation in this test permitted the full 8 ft of the tuner to be effective, the estimated LUF would be about 60 MHz. The SR data indicates that the LUF was greater than 100 MHz. It is probable that a larger tuner would result in a lower operational value for the LUF.

The uniformity of the chamber as a function of frequency is described in terms of the standard deviation of the average value of multiple measurements. The limited data collection time provided an opportunity to evaluate, at most, four different TX/RX configurations for some frequencies. Thus the data shown in Figure 12 represents a small statistical sample and should be used with caution. As is typical for other reverberation chambers, the uniformity is poorest at low frequencies. Tuner performance is a likely contributor to this effect. Above 500 MHz the standard deviation is less than 2 dB.

The modal structure was investigated in several bands over the frequency range 30 MHz to 8 GHz. As noted earlier, problems in the data acquisition software made it impossible to collect modal structure data from 60 to 90 MHz. Figure 13 shows the modal structure data for 1000 to 1003 MHz.

The modal structure is determined by the theoretical mode density and the cavity Q. The theoretical mode density depends on the frequency and the cavity dimensions. The effective mode density also depends on Q. When the cavity Q bandwidth, BW_Q, is less than the theoretical mode spacing, the theoretical mode density dominates. When the BW_Q is greater than the theoretical mode spacing, the Q effect dominates.[9] The theoretically predicted mode spacing was shown in Figure 4 and is repeated as the solid curve of Figure 14. The dashed line incorporates a K factor of five. The triangles in Figure 14 show the modal spacing deduced from data such as shown in Figure 13. As indicated in Figure 14, the modal structure in the cavity was generally in agreement with predictions based on empirical data from other reverberation chambers.
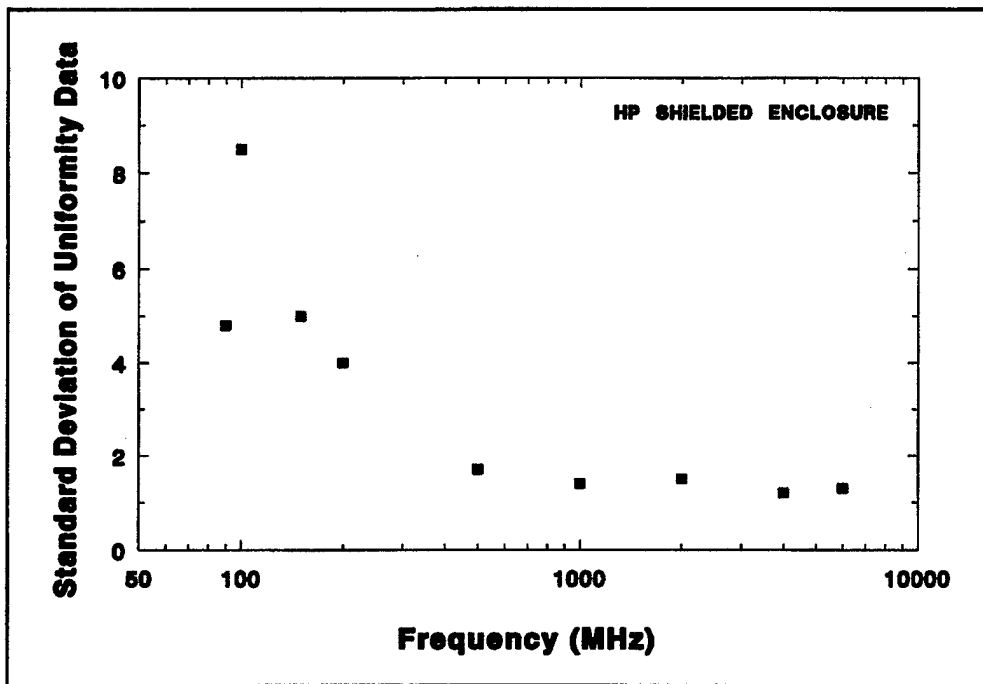
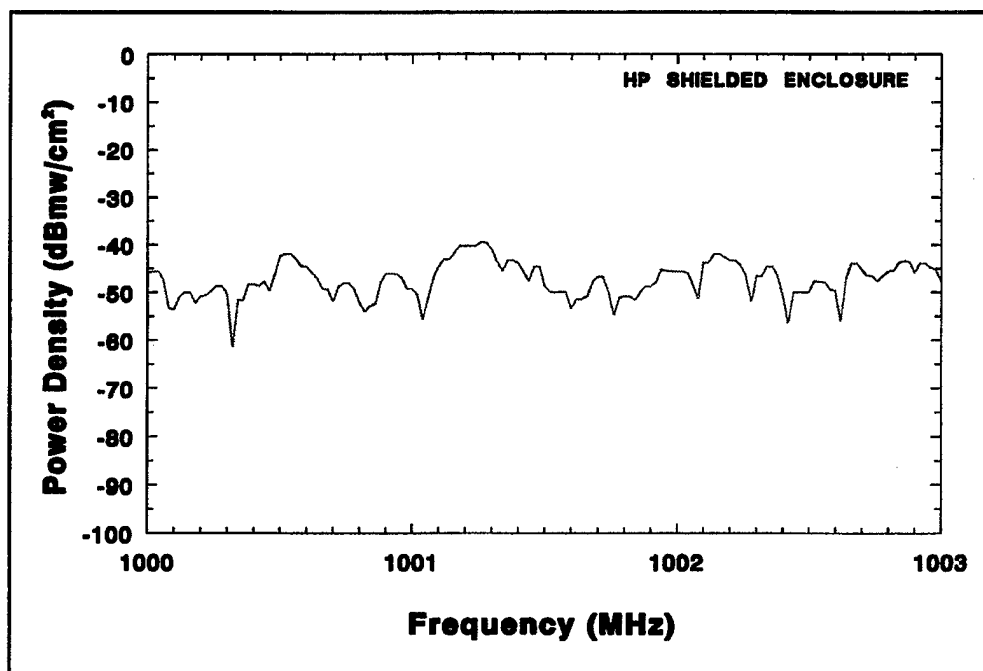FIGURE 12. STANDARD DEVIATION OF UNIFORMITY DATA AS
A FUNCTION OF FREQUENCY

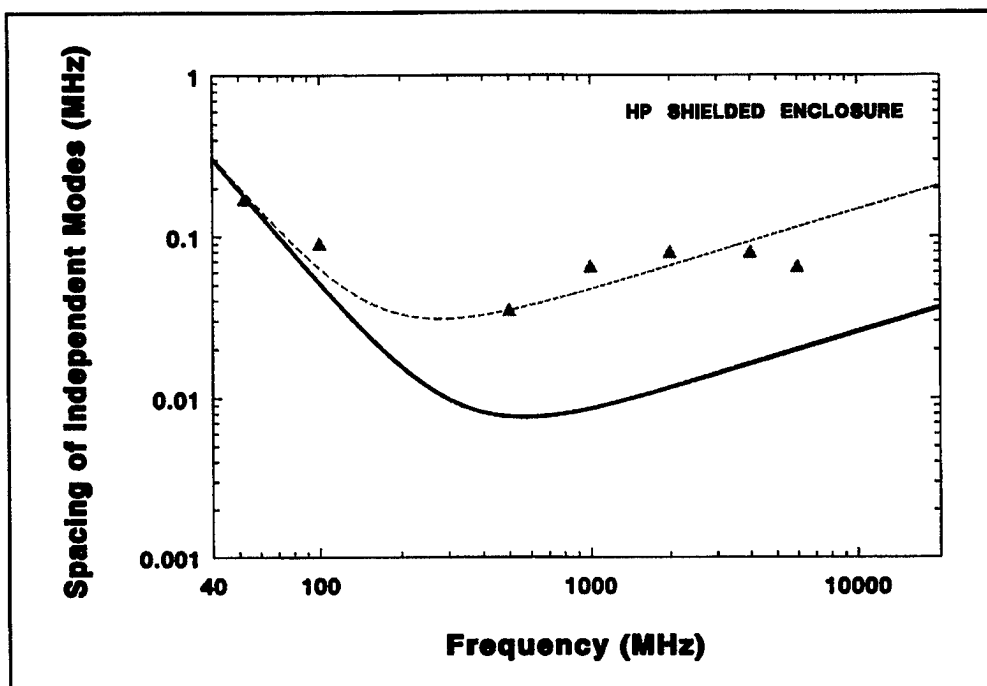

FIGURE 13. MEASURED MODAL STRUCTURE

FIGURE 14. MEASURED MODAL SPACING

4.0 CONCLUSIONS

Within measurement uncertainty:

- The statistical distribution functions were as expected and in agreement with theory. This indicates the cavity electromagnetic environment was isotropic and randomly polarized.

- The measured cavity quality factor was lower than expected. This could be attributed to several factors related to the test. The factors include unaccounted for loss mechanisms such as electrical conduits that penetrated the chamber at several points and various construction items and extensive runs of power cables which remained in the cavity during testing. Despite the lower values, the quality factor was high enough to allow generation of field levels of 200 V/m over a significant portion of the frequency band using only 200 watts of input power. The data suggest that for estimating achievable power densities, conservative extrapolation to larger chambers should have minimum risk.

- The lowest useable frequency was determined by the tuner and was approximately 100 MHz. A lower value should be obtainable with a larger tuner.

- The standard deviation of the chamber uniformity was less than 2 dB above 500 MHz.

- The modal structure was in general agreement with the predictions derived from the cavity dimensions and Q effects.

5.0 RECOMMENDATIONS

The following recommendations are offered:

- If the opportunity arises, perform a test on a large facility with a different wall material. A modular galvanized or a welded aluminum chamber should have a higher Q than the welded steel chamber tested. For a facility sized to test aircraft, a high quality factor would provide a significant benefit in the cavity power density versus input power tradeoff. However there may be cost differentials between the two materials. The scaleability in material effects is important to demonstrate.

- Develop a relatively strong structural framework system for constructing arbitrary sized tuners particularly at remote sites. This would permit matching the tuner to the common wavelength related guideline and would also permit investigation of the importance of the tuner size to cavity size ratio. The design should be easily assembled and disassembled and should be capable of providing a framework with variable sizing to at least twelve feet in the longest dimension. The framework would be covered with aluminum foil on-site and would rotate about a central shaft.

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